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Integrated Photonics (IP) Science Module for Ultra-wideband RF-optical Electro-magnetic Agility

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This document is the final technical report concerning the development of the Photonic ECM system in the framework of the project Integrated Photonics (IP) Science Module for Ultra-wideband RF-optical Electro-magnetic Spectrum (EMS) Agility phase I.
This final technical report intends to document and transmit the results of research and the work effort. Project objectives, work carried out, results obtained and technical description of development would be presented, along with acceptance test report including all relevant information about test setups and results obtained on 15th December 2015.

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Photonic ECM system

Integrated Photonics (IP) Science Module for Ultra-wideband RF-optical Electro-magnetic Agility

Final Technical Report

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1. INTRODUCTION

This document is the final technical report concerning the development of the Photonic ECM system in the framework of the project "Integrated Photonics (IP) Science Module for Ultra-wideband RF-optical Electro-magnetic Spectrum (EMS) Agility" phase I.

This final technical report intends to document and transmit the results of research and the work effort. Project objectives, work carried out, results obtained and technical description of development would be presented, along with acceptance test report including all relevant information about test setups and results obtained on 15th December 2015.

Abstract

Phase 1 has been developing successfully to the date and a full photonic countermeasures system implementing RGPO technique is being tested. Significant achievements have been reached, demonstrating fully transparent operation, ultra-low latency and wide instantaneous bandwidth, as well as reduction of size, weight and power figures comparing to conventional DRFM systems.

Broadband operation was demonstrated both with CW generators up to 40 GHz and with complex broadband radar waveforms, using chirp, frequency hopping and other agility parameters. Photonic RF filtering can be performed with 1-40 GHz continuous tunability, although more efforts should be put in order to improve the selectivity of the filtering, given the very small amount of fiber optic used for the application.

The potential applications of the research effort are the integration of new generation ECM deception systems with features beyond the today's equipment, being able to countermeasure modern radars and future realizations, open the door for integrating advanced self-protection system into new stealth platforms such as UAVs and small aircrafts and lead the way towards countermeasure even the latest missile guidance radar systems operating in the 100 GHz band.

2. PROJECT FOCUS AND OBJECTIVES

Current RF analysis systems employ electronics, often digital, such as Digital RF Memories (DRFM) devices, in which the RF is digitized and properly processed to analyze the in-coming signals. For high-frequency Comm, sensing, and radars such digital signals must be combined with RF down-converters, and for wideband operation, multiple digitizers are needed to cover the whole electro-magnetic spectrum (EMS). Photonics-based EMS sensing allows full RF-to-RF transparency with a frequency limitation only in the RF-Photonics (optical modulators) and Photonics-RF conversions (photodetectors), which are currently reaching 100 GHz. Such wide instantaneous bandwidth (i.e. 40 GHz RGPO technique for the module to be delivered in 2015) and beyond is not affordable in RF/digital technology. Using new ideas in fiber-optic technologies (for concept demonstration) and integrated photonics (in a second step for miniaturization, using SOI and SiN platforms) will be addressed.

The realization of well-know ECM techniques such as RGPO, VGPO or Cross-Eye using photonics technology requires implementing accurate delays, Doppler-shifts and phase-shifts for an instantaneous RF bandwidth of 40 GHz and beyond, which is not affordable in RF/digital technology. Both technologies fiber-optic (for concept demonstration) and integrated photonics (in a second step for miniaturization, using SOI and SiN platforms) will be addressed.

The approach is to exploit DAS access to unique combination of the fab and IP technologies at the Valencia Nanophotonics Technology Center (NTC), Silicon Nanofabrication Facility (an ISO 14644 facility), at the Universitat Politècnica de València. DAS will design the devices and testing interface of such on-chip science components such as active mode locked lasers, and electro-optic modulators/optical samplers with unprecedented instantaneous bandwidth, distortion, waveform flexibility, and polarization preservation, while using the university fab, cleanrooms and packaging facilities to find Si fab processing and chemistries that follow the solid state physics of InP or LiNbO3 on Si for improvements to components such as hybrid modulators. This device will be delivered to the Tri-Services.

The **objective** of the project is to design, develop, fabricate, and laboratory test new hybrid Integrated Photonics (IP)-based ultra-wideband (1 – 40 GHz, then 1-100 GHz) RF-to-Optical devices. Embed the device in a package that allows various inputs and analysis of the performance potential for IP to yield exceptional performance in RF--optical components for Electro-magnetic Spectrum (EMS) Agility. Deliver to DoD labs for testing.

3. SYSTEM DESIGN

Photonic ECM system performs RGPO (Range Gate Pull-Off) technique. This smart jamming algorithm is intended to produce false skin return signals to be received in a threat radar receptor which the user has decided to apply a countermeasure. For this technique to take effect, this false skin return must be produced with unsuitable RF transparency and low latency for a conventional electronic countermeasures system. The photonic ECM system developed in the framework of this contract uses electro-optical conversion and photonic treatment of the signal for returning perfect replicas of the radar signal, even when it is performing any ECCM technique as PRF staggering, frequency hopping or Intrapulse modulation.

For doing so, an architecture using hybrid RF and optical devices is used. Optical devices are used for broadband operation and optically delay and amplitude-control the signal, while RF electronics are used to drive optical devices and antennas to the best suitable level of operation. The Photonic ECM system block diagram can be shown in the following figure:

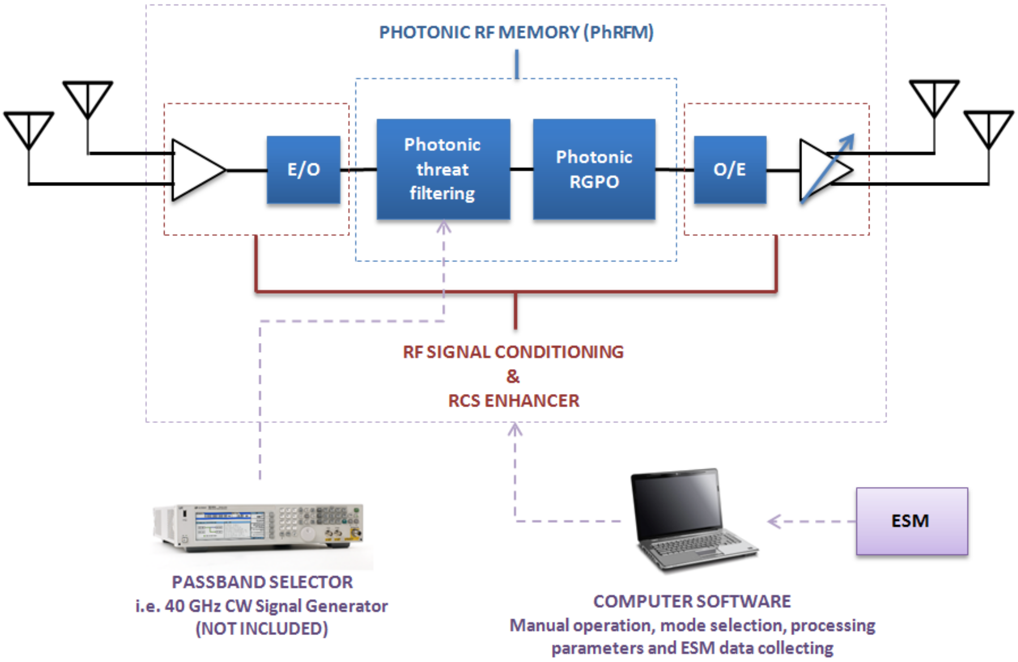

Figure 1: Photonic ECM system block diagram

The multiple blocks shown in the block diagram are described in detail in this section.

3.1. Subsystem description

The Photonic ECM system consists of 3 Line Replaceable Units (LRUs):

► **LRU #1**: **Antenna Assembly**

► **LRU #2**: **Photonic ECM Processor**

► **LRU #3**: **Mission Operator Control Station**

SYSTEM	LRU	SRU
Photonic ECM system	LRU#1 Antenna Assembly	SRU#1 LB Rx Antenna Unit
		SRU#2 LB Tx Antenna Unit
		SRU#3 HB Rx Antenna Unit
		SRU#4 HB Tx Antenna Unit
	LRU#2 Photonic ECM Processor	SRU#1 Wired Chassis
		SRU#2 Optical Link & Photonic Multiband Filter Module
		SRU#3 Optical Delay Line Module
		SRU#4 RF Module
	LRU#3 Mission Operator Control Station	COTS laptop

Table 1: Configuration of Photonic ECM system

Figure 2: LRUs in Photonic ECM system

3.1.1. LRU#1 Antenna Assembly

LRU #1: Antenna Assembly contains 4 modules (Shop-Replaceable Units: SRUs) as described in the following table. It can be noted that signals are channelized in 1-18 and 18-40 GHz sub-bands for COTS antenna matching. Cavity-backed spirals are selected instead of other antennas due to great beam width consistency along the whole bandwidth of operation. Also, transmitting and receiving antennas are polarization-diversified for maximum isolation.

LRU	SRU	Description
LRU#1 Antenna Assembly	SRU#1 LB Rx Antenna Unit	1-18 GHz Cavity-backed spiral antenna, used for RF reception in the low band. Left hand circular polarization.
	SRU#2 LB Tx Antenna Unit	1-18 GHz Cavity-backed spiral antenna, used for RF transmission in the low band. Right hand circular polarization.
	SRU#3 HB Rx Antenna Unit	18-40 GHz Cavity-backed spiral antenna, used for RF reception in the high band. Left hand circular polarization.
	SRU#4 HB Tx Antenna Unit	18-40 GHz Cavity-backed spiral antenna, used for RF transmission in the high band. Right hand circular polarization.

Table 2: Description of Antenna Assembly SRU modules.

Figure 3: LB and HB spiral antennas

3.1.2. LRU#2 Photonic ECM Processor

LRU #2: Photonic ECM Processor contains 3 modules (Shop-Replaceable Units: SRUs) plus the Wired Chassis.

Figure 4: Photonic ECM Processor

3.1.2.1. SRU#1 Wired Chassis

Figure 5: Wired Chassis

The **Wired Chassis houses the modules with VME form factor** and is the mechanical structure of the Photonic ECM system

The Wired Chassis is an aluminum structure made to support all other modules. It contains a motherboard where multi-pin connectors are installed

All the internal modules of the Photonic ECM connect to these connectors

The motherboard give data and power supply to all the modules

3.1.2.1. SRU#2 Optical Link & Photonic Multiband Filter Module

This module performs the E/O and O/E conversions, admitting the Radio Frequency (RF) signals at its input and delivering it back after the photonic processing

It controls the application of RF-photonic filtering to counter selected threats

Figure 6: Optical Link & Photonic Multiband Filter Module

3.1.2.1. SRU#3 Optical Delay Line Module

It includes the Photonic RF Memory (PhRFM) carrying out the generation of ECM techniques: RGPO.

3.1.2.1. SRU#4 RF Module

RF Module is intended to perform RF level conditioning for optimum electro-optical conversion dynamics, as well as providing antenna assembly connectivity by combining and splitting signals from and to antenna sub-bands (1-18 + 18-40 GHz)

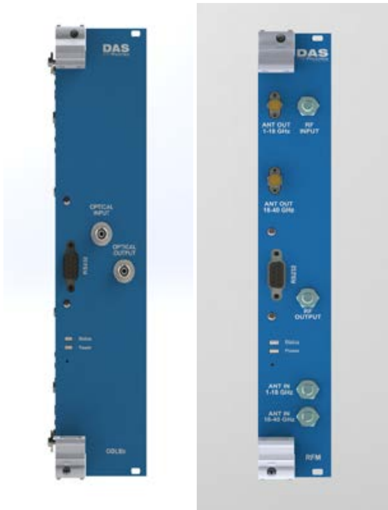

Figure 7: Optical Delay Line and RF Modules

3.1.3. LRU#3 Mission Operator Control Station

LRU #3: Mission Operator Control Station is a Commercial Off the Shelf (COTS) laptop. It provides Human Machine Interface and includes ELINT software interfacing to enable threat data transfer to the ECM.

Figure 8: Mission Operator Control Station

3.2. ECM operation

RGPO is a deception jamming technique used against tracking radars, with the objective of moving the range gate onto an erroneous range and force loss of track and reacquisition in the threat radar to be countermeasured. Up to now, it has been the principal technique employed in self-defense. It is generally very effective especially against automatic tracking systems.

In the absence of an operator to spot the deception and lead the range back onto the true target, it is enough to lead the radar range gate away from the real echo and then to deactivate the transmission of the deception signal itself. Once break-lock has been achieved, the radar must start the search and acquisition phases before it can continue tracking, thus losing time.

RGPO may be countered effectively by radar with an ECCM technique called anti-range gate stealing (ARGS), or leading-edge tracking. This ECCM technique uses latency of the RGPO to keep on track of the original pulse even when other false echoes are summed. Conventional ECM systems have a typical minimum delay of approximately 200ns due to the time DRFM needs to digitize, save and reproduce the signal. DAS Photonics' ECM system can improve this time significantly as it does not need any digitalization for applying broadband delays to any signals. As only analog propagation through the system is needed, very low latency figures can be achieved, especially when designing a dock nanoswitches.

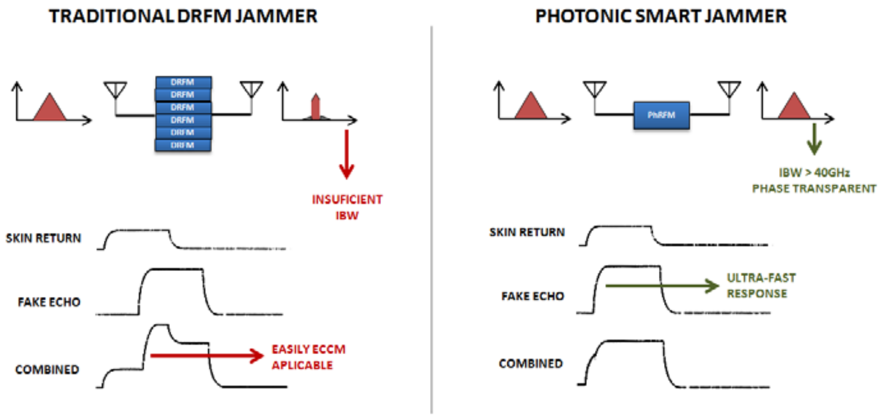

Figure 9: Diagram showing main differences between traditional and photonic signal processing.

Using frequency, pulsewidth or PRF agility can be used by radar to counter-countermeasure RGPO technique by forcing the RF memory of the jammer to reach instantaneous bandwidth or pulsewidth away from its maximum operating capabilities. This is due to Digital RF Memories (DRFM) architecture, which uses frequency conversion and digitalization with limited instantaneous bandwidth and limited memory length in order to try to reproduce original signal. This is not the case for photonic processing, as it performs broadband operation along 40 GHz bandwidth.

Also, traditional DRFM-based ECM processors need to use channelized receptors in order to achieve frequency coverage up to 40 GHz. This leads to great decrease of SWaP of the systems, since most hardware needs to be replicated.

The developed system exhibits two selectable input scales to allow enhanced dynamic range capability. This leads to its ability to countermeasure either powerful or weak incoming signals and optimize output signal linearity.

- Low power mode, for input powers ranging from -80 to -30 dBm
- High power mode, for input power ranging from -40 to 10 dBm.

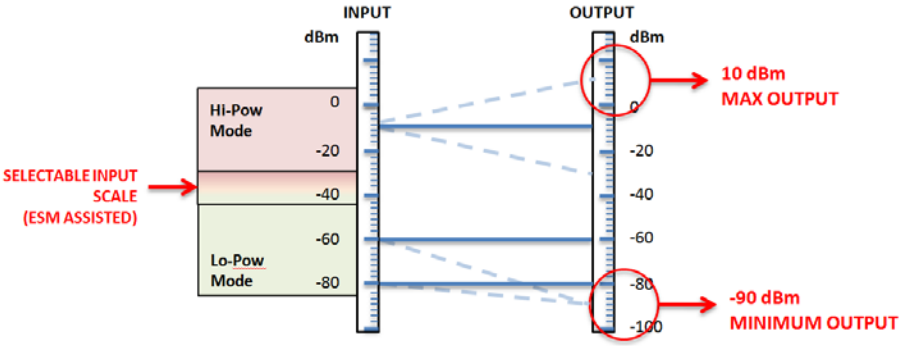

Figure 10: Diagram showing selectable input scale ability of the system

Also, the system implements two different modes of operation, depending on the threats it can countermeasure simultaneously:

- Transparent mode, in which all incoming signals are countermeasured at once. This mode is especially useful for threats with very broadband behavior or unknown threats.
- Selective mode, in which photonic threat filtering is applied in order to eliminate undesired signal from the output.

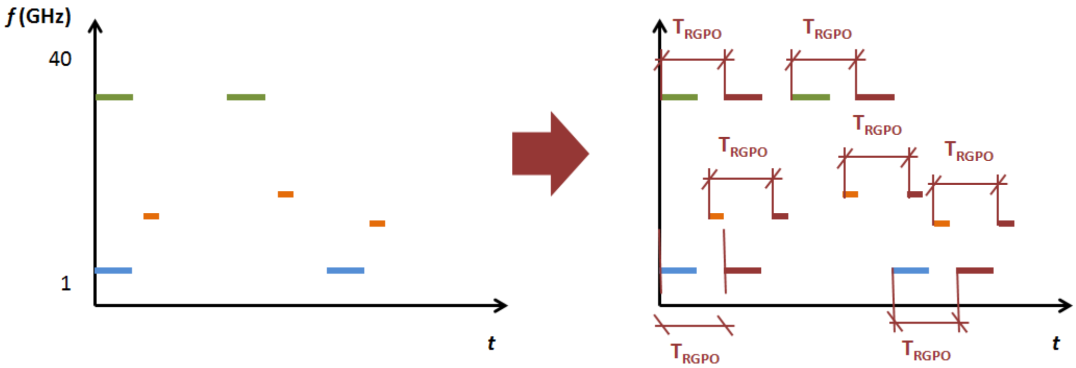

Figure 11: Diagram showing transparent mode of operation principle

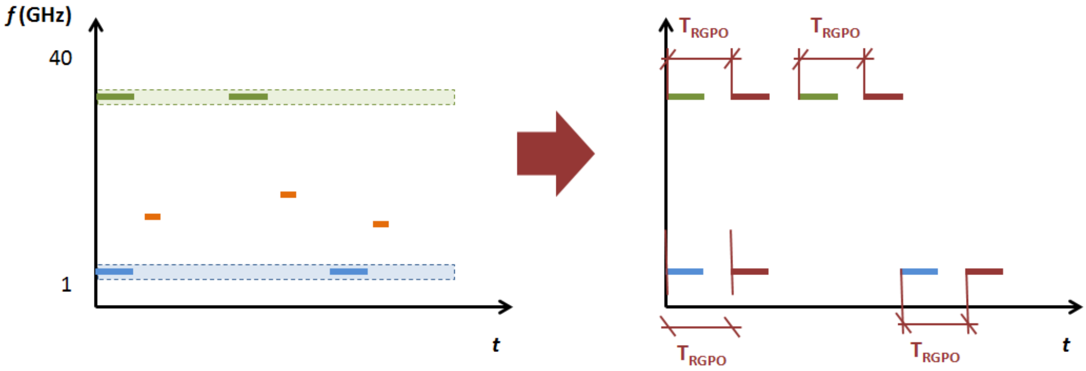

Figure 12: Diagram showing selective mode of operation principle

3.3. SWAP analysis

This section intends to present size, weight and power analysis of the system (SWaP), being made as an exhaustive calculation of every component features. For better understanding of the photonics, electronics and mechanics limits, the calculations are grouped by component family and by system module.

3.3.1. Weight per module

The following table includes the distribution of weight among different SRU (modules). From the table can be extracted that the biggest amount of weight is due to wired chasis, as it is natural. This includes power supply, mechanics, backplane connecting different modules, etc. The system modules hold the rest of the weight of the system in approximately equal quantities. This results are also shown in the next figure as a diagram.

WEIGHT - BY MODULE		
	Weigth (g)	**Contrib (%)**
SRU #1 Wired chasis	**1240**	**30.89380255**
Backplane	300	7.474307069
Power supply	440	10.96231704
Others	500	12.45717845
SRU #2 Optical link + Photonic Multiband Filter	**1105.17**	**27.53459981**
Photonic components	504.31	12.56455933
RF components	87.9	2.189971971
PCBs	265.74	6.620741202
Mechanical (shielding, heatsinks...)	247.22	6.159327312
SRU #3 Optical delay line	**753.01**	**18.76075989**
Photonic components	334.6	8.336343818
PCBs	132.87	3.310370601
Mechanical (shielding, heatsinks...)	285.54	7.114045469
SRU #4 RF Module	**915.57**	**22.81083775**
RF components	540.2	13.4587356
PCBs	132.87	3.310370601
Mechanical (shielding, heatsinks...)	242.5	6.041731548
TOTAL	**4.01375**	**kg**

Table 3: Distribution of weight SRUs

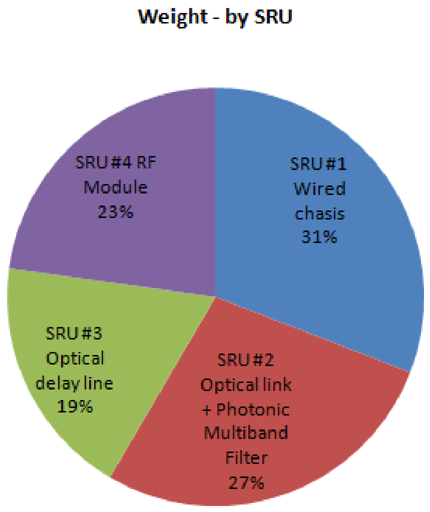

Figure 13: Weight distribution per SRUs in Photonic ECM Processor

3.3.2. Weight & Power consumption per component family

The following table and diagrams show both weight and power consumption grouped by component family. It can be seen that weight is mostly due to mechanical elements, as it was expected. Power consumption is due mostly to amplification devices, RF output amplifiers in particular. Although a similar quantity of power consumption is due to photonic components, this is only true when photonic filtering is being applied, which should not be the case for continuous operation.

POWER & WEIGHT - BY FAMILY		
	Weight (g)	Power (W)
Photonic components	838.91	23.28
RF components	628.1	23.52
PCBs / Control electronics	531.48	10
Backplane	300	5
Mechanicals	1275.26	-
Power supply	440	-
TOTAL	**4013.75**	**61.8**

Table 4: Distribution of weight & power per component family

Also, the photonic ECM system features a power management firmware devoted to ensure proper power consumption by switching off amplification always a RGPO technique is stopped by the user.

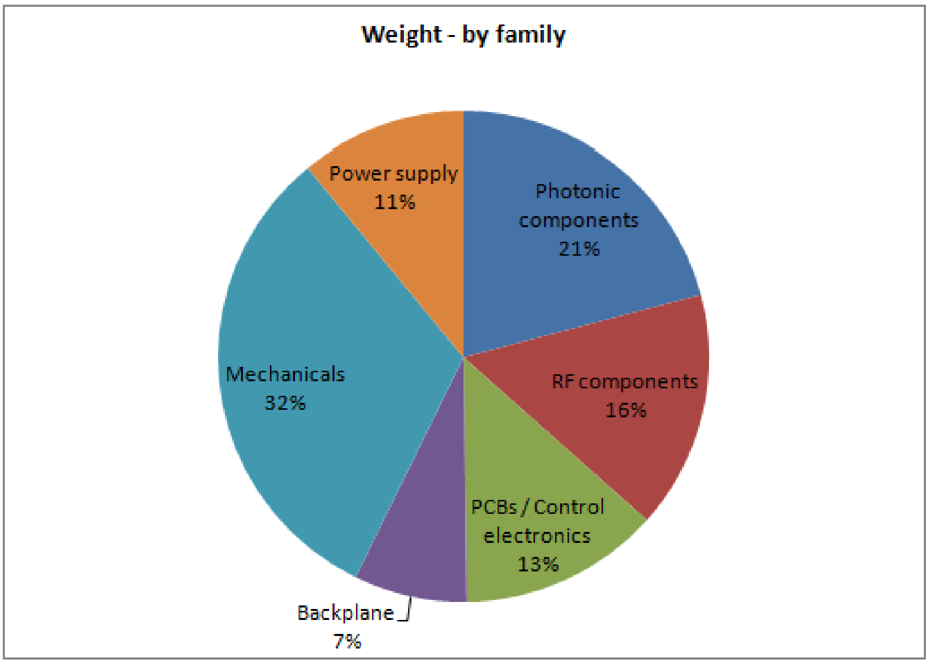

Figure 14: Weight per family

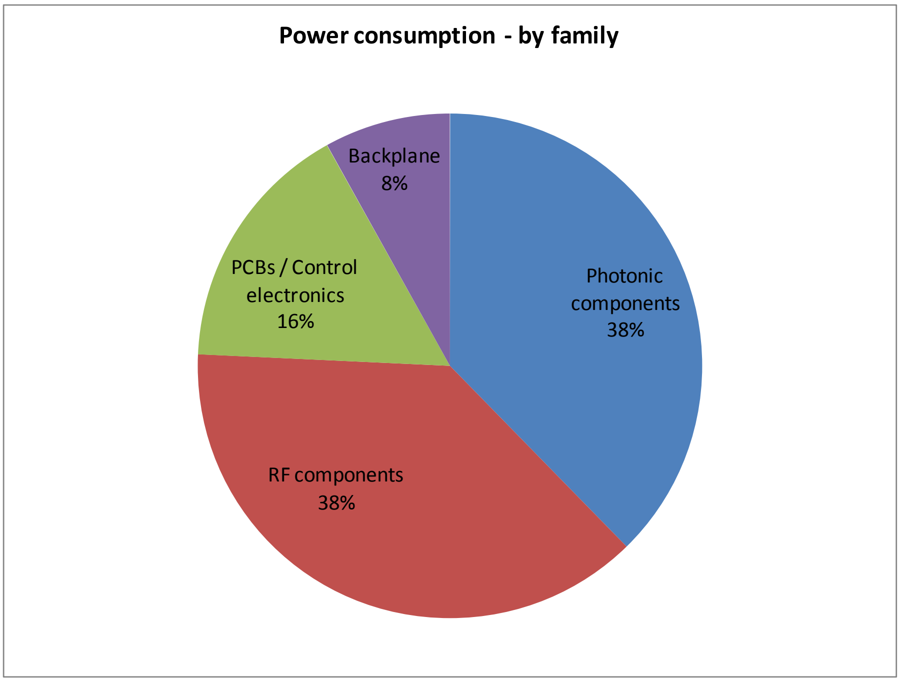

Figure 15: Power consumption per family

3.4. Human Machine Interface

The human-machine interface for the control of Photonic ECM system is prepared to be connected to the system by a serial port. Once connected, the human-machine interface running in any laptop is able to perform the operations that are described in the following lines.

The ECM interface is integrated in an ELINT system software, as an upgrade module to have both systems controlled simultaneously. This is useful for the proper configuration of the ECM system depending on the measured parameters of the threat to countermeasure. The following figure shows the “ECM” module as an option among others in this ELINT software:

Figure 16: Module selection in the ELINT software, including ECM control module

ELINT data integration in the human-machine interface prepared for the control of the ECM system could be used in the configuration of the ECM system as explained in the following points:

- ECM system input scale will be set according to the detected power level for the threat to be countermeasured. This way, extended dynamic range capability of the system can be exploited and minimum distortion of the input signal is performed.
- Providing the user has a proper countermeasures library, in which the optimum spoofing pattern for a threat is described, the ECM system will apply it when performing RGPO technique. This ensures optimum gate stealing and deception for each individual radar, given their different ALC circuitry, dynamic range, etc.
- Photonic threat filtering will be set to the central frequency of the threat to countermeasure, providing the user has defined the “Selective” mode of operation.

The following figure shows the main window for controlling the system, in which the user can find the following elements:

1. Threat table, including data from ELINT sensor connected to the computer. In this standalone demo system, this table is filled with example threats to be deceived.
2. “Start deception” button, with which RGPO technique is launched just as shown in the spoofing pattern descriptor (5).
3. “Manual deception” button, with which the user can set specific gain, delay, input scale and center frequency filtering static settings and send it to the system.
4. Gain/Range display, showing actual state of gain and range deception being applied by the system. Deception distance in meters is shown also in the combo-box detailed in the screenshot.

5. Spoofing pattern display: this group of elements shows the deception pattern to be applied when pulsing “Start deception” (2). The spoofing pattern can be edited just pulsing “Edit spoofing pattern” button, which will open the proper dialog.
6. System status display, showing any possible alarm being delivered by the system.
7. “Operation mode” selector, being able to select between “Transparent” and “Selective”
8. “Scale” selector, being able to select between low or high input power.

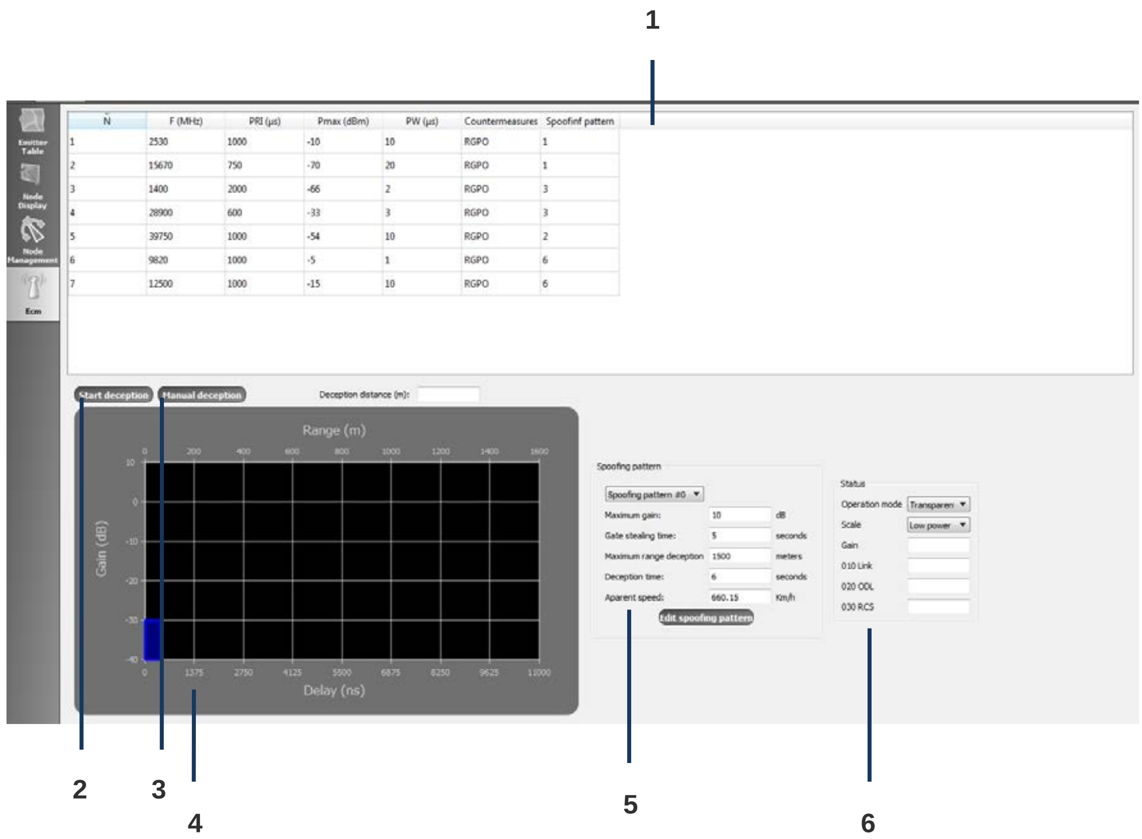

Figure 17: Main ECM system control window

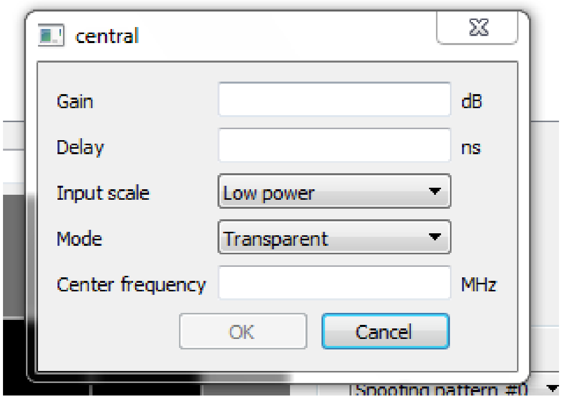

Figure 18: Manual settings dialog

The previous figure shows the simple “Manual deception” dialog, in which Gain, Delay, Input scale, Mode and Center frequency can be set and send to the system. Automatically, the system will set the desired status if the introduced parameters are among the possible values.

The following figure shows the spoofing pattern editing dialog. In this dialog, the gain and delay slopes to be applied in the deception can be seen and edited using the parameter shown below. The traces will change accordingly with the parameters introduced, and Apparent speed for the deceived radar calculated. Spoofing patterns can be loaded from those saved in the software memory only by selecting the pattern in the list, and any modification can be both overwritten or saved as a new pattern.

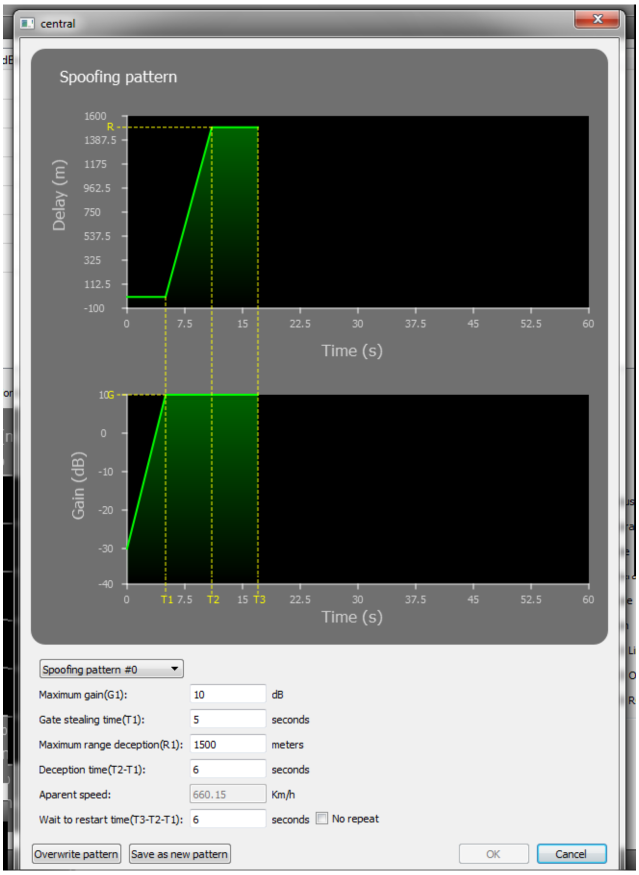

Figure 19: Spoofing pattern editing dialog

Also, the software includes an auto-detection of the serial port connected to the system. If the system is not connected properly, then a warning will show for the operator to be aware. This is shown in the following screenshot:

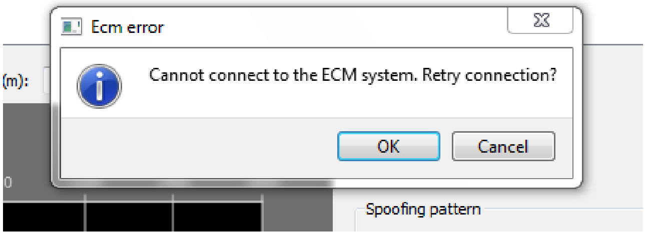

Figure 20: “ECM disconnected” warning

3.5. Integrated photonics development

Integrated photonics development has been done to improve optical delay line switching architecture. COTS switches used by DAS Photonics for the standard optical delay line are 2x2 independent MEMs switches. This architecture has the disadvantage of being much less efficient both in size and in power consumption compared with silicon-on-insulator solutions for light switching. With the same functionality, custom designs can be done to integrate the full architecture in a single photonic chip and reach performances beyond the state of the art in optical delay lines. The conceptual design of such chip is shown in the following figure:

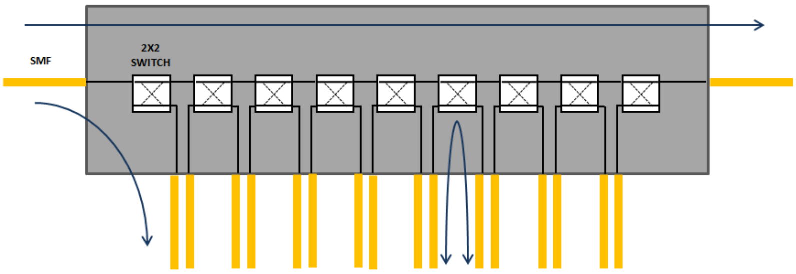

Figure 21: Conceptual design of the chip integrating the full delay line switching architecture.

The following table gathers the advantages of using integrated nanoswitches instead of COTS MEMs switches:

Description	MEMs COTS	Integrated nanoswitches
Architecture	9 x 2x2	Only 1
Peak power consumption	170 mW	< 10 mW
Maximum repetition rate	< 1 kHz	< 10 MHz
Response time (rise, fall)	< 10 ms	< 10 us
Programmable delay line minimum delay	100 ns	40 ns

Table 5: Performance comparison between COTS MEMs switches and integrated nanoswitches

Countermeasurement performance is greatly affected by this design, especially for the minimum delay able to be obtained. Having all switches integrated in a single chip reduces the cumulative group delay produced by the sum of the pigtails of the nine successive COTS switches. Even doing the best effort in reducing the pigtails length by doing very tight fiber splices, it is a minimum delay which is possible to achieve when having separated fiber devices. When integrated, the cumulative group delay of the waveguides between switches become neglectable and the limiting group delay in the system is due to the rest of the components of the optical link (components pigtails, modulators, EDFA…).

The first considered design solution was 200nm SOI with 400nm rib waveguide. This is the typical configuration for these devices in the used fabrication process, which is illustrated in the following figures.

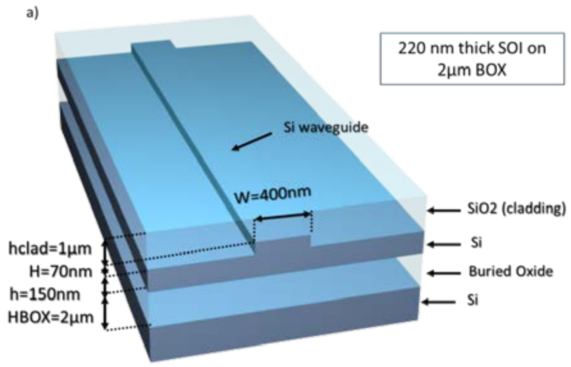

Figure 22: Diagram showing the first design of selected waveguides

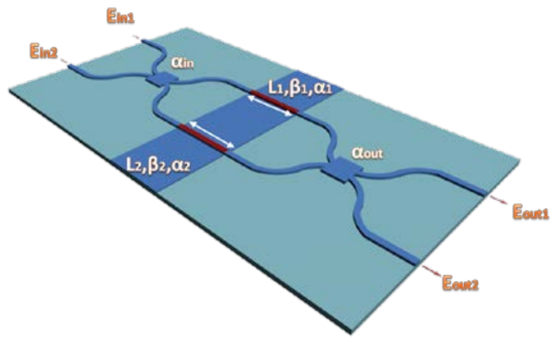

Figure 23: Diagram showing nanoswitch structure

Nevertheless, excessive insertion loss are obtained due to the difficulty of fiber coupling in such small waveguides. For overcoming this problem, the following alternative technologies were studied to fit the insertion loss requirements:

- Buried Ge-doped oxide waveguide (low contrast)
- SiN waveguides
- Thicker SOI (400nm instead of 220nm)

Finally, using a thicker SOI was considered as the best option due to the silicon ability to achieve the best switching speeds and full compatibility with CMOS processes. The following table include the loss estimation of a switch being fabricated in standard (220nm) and thicker (400nm) SOI. As it can be extracted from the table, very significant improvements are achieved in this regard. Lower insertion loss impacts very directly in countermeasurement performance, as they affect the optical RF link overall gain and, therefore, all significant RF dynamic performance of the system (minimum detectable signal, noise figure…).

Building blocks	220nm SOI Loss (dB)	400nm SOI Loss (dB)
90º bends	8x 0.1=0.8 dB	8x 0.1=0.8 dB
2x2 MMI 3dB couplers	2x 0.5=1 dB	2x 0.5=1 dB
2 tapers	2x 0.5= 1 dB	2x 0.5= 1 dB
Waveguide	5x 0.1=0.5 dB	0.5x 0.1=0.05 dB
On-state (carrier injection)	0.5 dB	0.5 dB
On chip Loss	**3.7 dB**	**3.25 dB**
I/O coupling	2x 4.5=9 dB	2x 1=2 dB
Fiber-to-fiber loss	**12.7 dB**	**5.25 dB**

Table 6: Comparison between standard SOI and thicker SOI switches insertion losses

The following figure shows the preliminary design of a 3 switch chain:

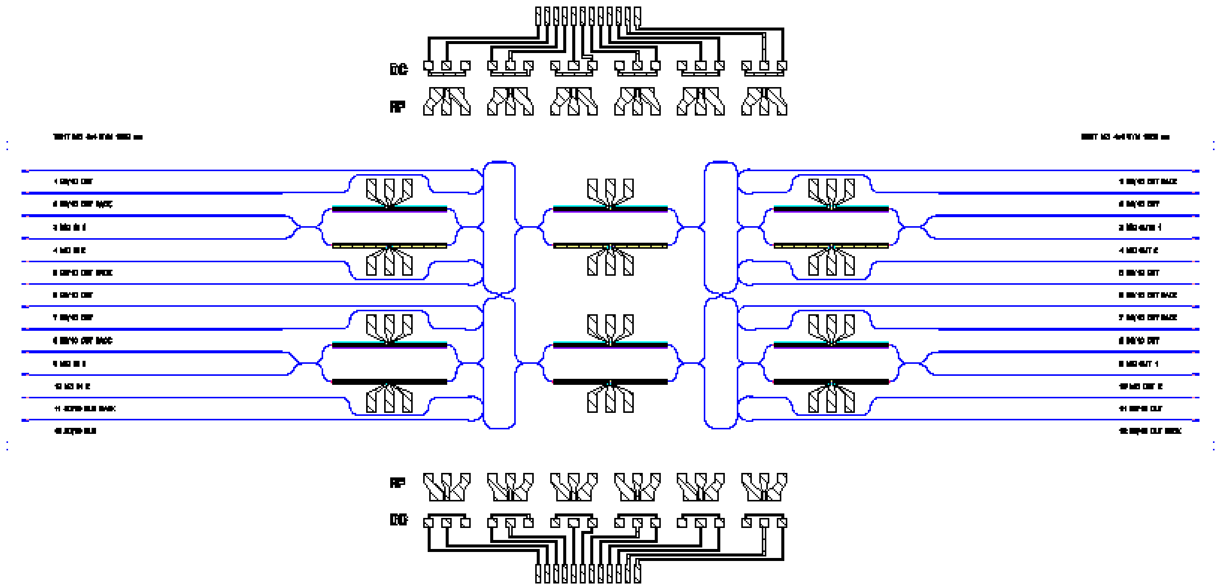

Figure 24: Preliminary design of a 3 switch chain

Also, this table gathers all the significant design notes regarding the differences between 200nm SOI and 400nm SOI:

	<1um rib waveguide	>1um rib waveguide
Losses	1-5dB/cm	0.2-0.5dB/cm
90º Bends mínimum radius	30um	1mm
Polarization dependence	High	Low
Single operation	Yes	Under certain conditions
Speed	Multi GHz	GHz achievable

Table 7: Comparison between standard SOI and thicker SOI waveguides in its design considerations

4. WORK PROGRESS

4.1. Test setup description

The following figures show the different scenarios used in the Test Cases included in the Acceptance Test Procedure.

Test Scenario	Description
Test Scenario #1	A single radar emitting pulses at several PW and PRI values, corresponding to different radar ranges, powers and distances.
Test Scenario #2	Two radars overlapping with different frequency.

Table 8: Description of Test Scenarios

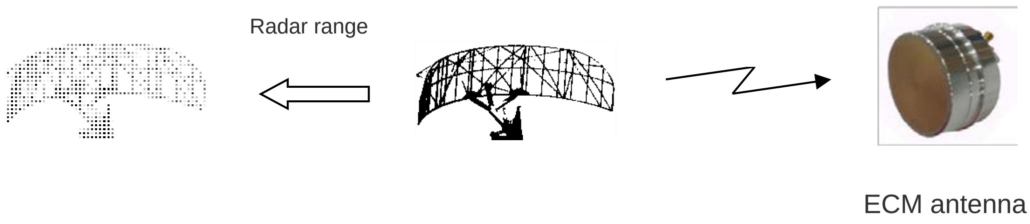

Figure 25: Test Scenario 1

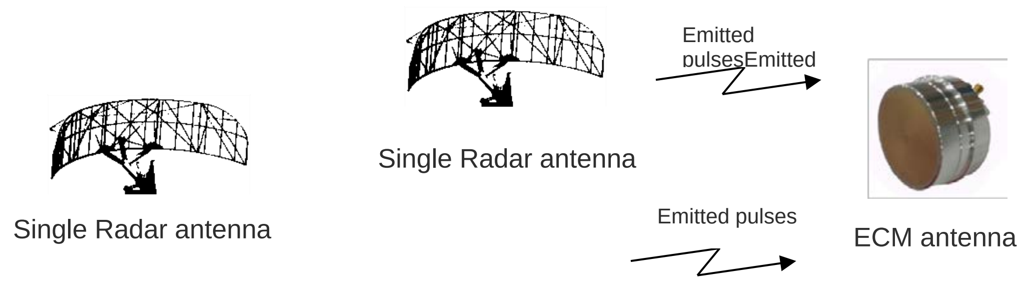

Figure 26: Test Scenario 2

The following figures show the different Test Set-Up used in the Test Cases included in the Acceptance Test Procedure.

Test Set-Up	Description
Test Set-Up #1	A typical set-up to measure analog RF dynamic characteristics.
Test Set-Up #2	A typical set-up to measure analog RF instantaneous bandwidth characteristics, including two signal generators for performing its independent reception.

Test Set-Up #3	In order to simulate a radar, a signal generator is used to provide I/Q signals to a RF pulse generator. The output of the RF pulse generator feeds the input of the ECM system. Once signal has been processed, output of ECM system is downconverted using a typical superheterodyne receptor included in the spectrum analyzer by properly setting up its LO and resolution bandwidth parameters. The IF output of the spectrum analyzer is then introduced in a digital oscilloscope to observe processed baseband pulses.
Test Set-Up #4	In order to simulate different radars using broadband intrapulse modulation, frequency hopping or PW/PRI agility, the signal generator is used as the feed of ECM system directly. This way, the full instantaneous bandwidth of the generator can be used and read the output processed signals using the digital oscilloscope.
Test Sep-Up #5	The network analyzer will be used to demonstrate threat filtering capabilities, along this a CW generator as a passband selector tuner.

Table 9: Description of Tests Set-Up

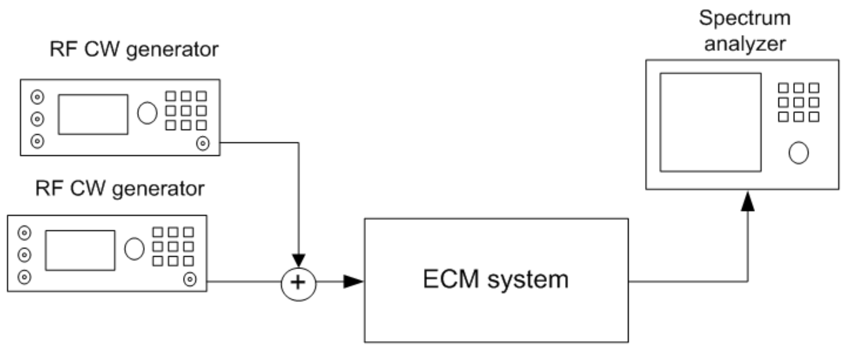

Figure 27: Test Set-Up no.1

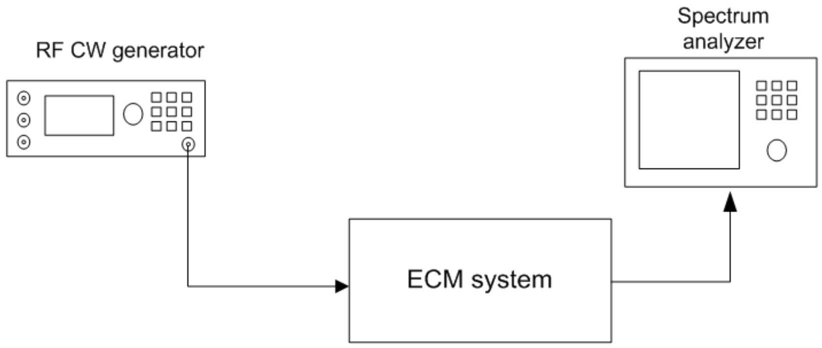

Figure 28: Test Set-Up no.2

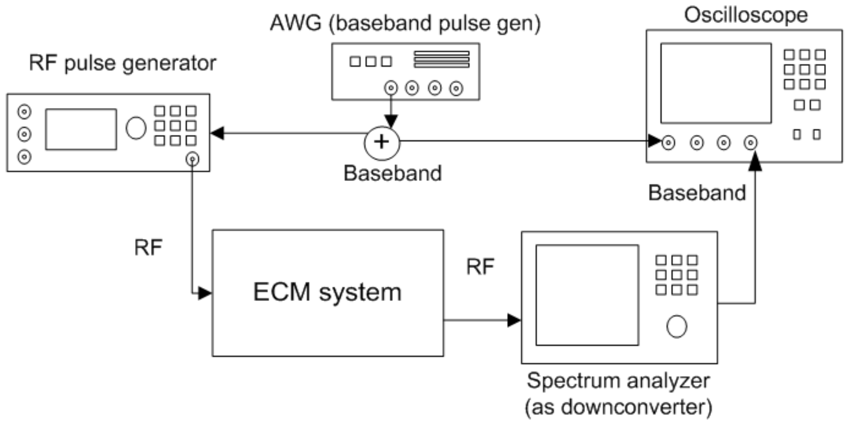

Figure 29: Test Set-Up no.3

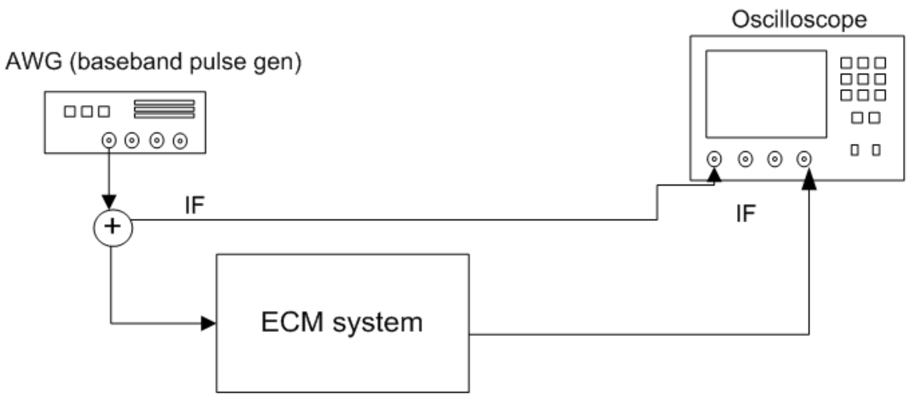

Figure 30: Test Set-Up no.4

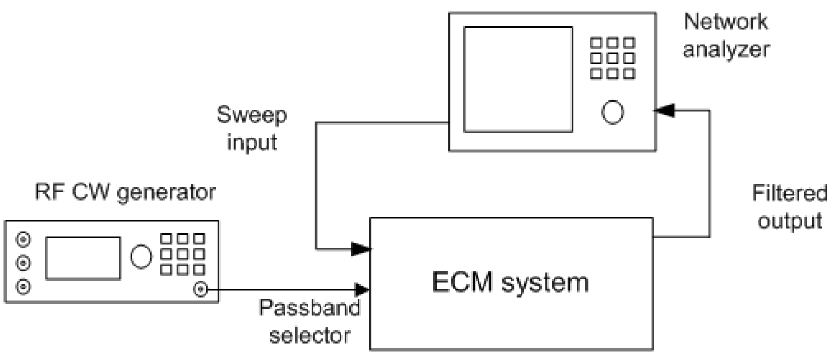

Figure 31: Test Set-Up no.5

4.2. Acceptance test report

Most of the tests proposed in the Acceptance Test Plan document were performed in 15th December 2015, which are included in the following tables:

4.2.1. Optical delay line measurement

Test Case	TC_0040			
Purpose	This test aims to measure optical delay line specifications such as minimum delay, resolution, maximum delay and number of bits.			
Scenario	No scenario is applicable.			
Test Set-Up	According to Figure 29. The set-up will generate pulsed signals with any desired characteristics and frequencies up to 40 GHz, within the AWG bandwidth. Then, pulsed signals would be received using a downconverter and time measurements will be performed in a digital oscilloscope. For uniformity, all pulsed signals will have 1us pulsewidth, 50us PRI, -30dBm average power and no chirp. The downconverter LO will always be set to obtain a constant 20.4 MHz IF signal, with 1MHz resolution bandwidth and proper input scale.			
Test Goal	Measure time delay values compliant with specifications. A measurement resolution of 10ns should be taken into account in the assessment of this test.			
Test Procedure	**Id**	**ACTION**	**Generated Freq (GHz)**	**Optical delay line bit setup (ns)**
Step 1	040.1	ENTER	2	0
		ENTER		1500
		ENTER		2500
		ENTER		10000
Step 2	040.2	ENTER	10	0
		ENTER		1500
		ENTER		2500
		ENTER		10000
Step 3	040.3	ENTER	40	0
		ENTER		1500
		ENTER		2500
		ENTER		10000

Test Results	**Id**	**ACTION**	**Measured delay (ns)**	**Expected result**	**Pass**
Step 1	040.1	VERIFY	97	100	OK
		VERIFY	1560	100 + 1500	OK
		VERIFY	2560	100 + 2500	OK
		VERIFY	9530	100 + 9472	OK

Step 2	040.2	VERIFY	97	100	OK
		VERIFY	1560	100 + 1500	OK
		VERIFY	2560	100 + 2500	OK
		VERIFY	9530	100 + 9472	OK
Step 3	040.3	VERIFY	97	100	OK
		VERIFY	1560	100 + 1500	OK
		VERIFY	2560	100 + 2500	OK
		VERIFY	9530	100 + 9472	OK
Go To	TEST CASE 0050				

4.2.2. RGPO performance

Test Case	TC_0050			
Purpose	This test is intended to demonstrate the ECM system RGPO technique generation against a fixed frequency pulsed radar.			
Scenario	According to Fig. 25. Fixed frequency radar is tracking the ECM platform and then it is counter-measured by the ECM system using RGPO gate stealing technique.			
Test Set-Up	According to Figure 29. The set-up will generate pulsed signals. For uniformity, all pulsed signals will have 1us pulsewidth, 50us PRI, -30dBm average power and no chirp. The downconverter LO will always be set to obtain a constant 20.4 MHz IF signal, with 1MHz resolution bandwidth and proper input scale.			
Test Goal	Certify that RGPO technique is performed as expected.			
Test Procedure	**Id**	**ACTION**	**Generated Freq (GHz)**	**Spoofing pattern**
Step 1	050.1	ENTER	10	#1
Step 2	050.2	ENTER	20	#2
Step 3	050.3	ENTER	35	#3
Test Results	**Id**	**ACTION**	**Check**	**Pass**
Step 1	050.1	VERIFY	OK	OK
Step 2	050.2	VERIFY	OK	OK
Step 3	050.3	VERIFY	OK	OK
Go To	TEST CASE 0080			

4.2.3. Broadband radars signals processing

Test Case	TC_0060
Purpose	This test is intended to demonstrate the ECM system RGPO technique generation against a different kind of agile modern pulsed radars.
Scenario	According to Fig. 25. A modern radar is tracking the ECM platform and then it is counter-measured by the ECM system using RGPO gate stealing technique.
Test Set-Up	According to Figure 30. The set-up will generate pulsed signals with any desired characteristics and frequencies up to 625 MHz, within the AWG bandwidth. No upconversion is performed because of the low instantaneous bandwidth of the receiver downconverter used for pulse visualization.
Test Goal	Certify that RGPO technique is performed as expected even with very agile radars.

Test Procedure	**Id**	**ACTION**	**Signal description**	**Center Freq (MHz)**	**PW (us)**	**PRI (us)**
Step 1	060.1	ENTER	Chirped signal – 300 MHz sweep	300	20	120
Step 2	060.2	ENTER	Frequency hopping signal among 300 MHz bandwidth	300	1	120
Step 3	060.3	ENTER	PRI agility – level 8	300	1	Agile
Step 4	060.4	ENTER	PW agility – level 8	300	Agile	120
Step 5	060.5	ENTER	Frequency hopping among 300 MHz bandwidth + PRI agility + PW agility	300	Agile	Agile

Test Results	**Id**	**ACTION**	**Check**	**Pass**
Step 1	060.1	VERIFY	OK	OK
Step 2	060.2	VERIFY	OK	OK
Step 3	060.3	VERIFY	OK	OK
Step 4	060.4	VERIFY	OK	OK
Step 5	060.5	VERIFY	-not generated-	
Go To	TEST CASE 0110			

4.2.4. Threat filtering demonstration

<table>
<tr><td>Test Case</td><td colspan="5">TC_0070</td></tr>
<tr><td>Purpose</td><td colspan="5">This test is intended to demonstrate the ECM threat filtering capability. Since threat filtering is still a limited functionality, no acceptance requirement is applied in this test. This demonstration is only performed as an evaluation for future research on photonic widely tunable passband filtering.</td></tr>
<tr><td>Scenario</td><td colspan="5">According to Fig. 26. Two fixed frequency radars are delivering pulses to the platform where the ECM system belongs. ECM system filters out one of the threats to countermeasure only one of them.</td></tr>
<tr><td>Test Set-Up</td><td colspan="5">According to Figure 31. Photonic RF filtering will be demonstrated using the network analyzer and passband selector CW generator.</td></tr>
<tr><td>Test Goal</td><td colspan="5">Certify threat filtering is performed, showing a certain elimination of non-filtered threats. Also, automatic command of passband selector instrumentation is shown here.</td></tr>
<tr><td>Test Procedure</td><td>Id</td><td>ACTION</td><td>Center Freq (GHz)</td><td colspan="2">Span (GHz)</td></tr>
<tr><td>Step 1</td><td>070.1</td><td>ENTER</td><td>3</td><td colspan="2">0.4</td></tr>
<tr><td>Step 2</td><td>070.2</td><td>ENTER</td><td>12</td><td colspan="2">0.4</td></tr>
<tr><td>Step 3</td><td>070.3</td><td>ENTER</td><td>40</td><td colspan="2">0.4</td></tr>
<tr><td>Test Results</td><td>Id</td><td>ACTION</td><td colspan="2">Check</td><td>Pass</td></tr>
<tr><td>Step 1</td><td>070.1</td><td>VERIFY</td><td colspan="2">-demonstrated full span tunability, see figure-</td><td></td></tr>
<tr><td>Step 2</td><td>070.2</td><td>VERIFY</td><td colspan="2">-demonstrated full span tunability, see figure-</td><td></td></tr>
<tr><td>Step 3</td><td>070.3</td><td>VERIFY</td><td colspan="2">-demonstrated full span tunability, see figure-</td><td></td></tr>
<tr><td>Go To</td><td colspan="5">TEST CASE 0110</td></tr>
</table>

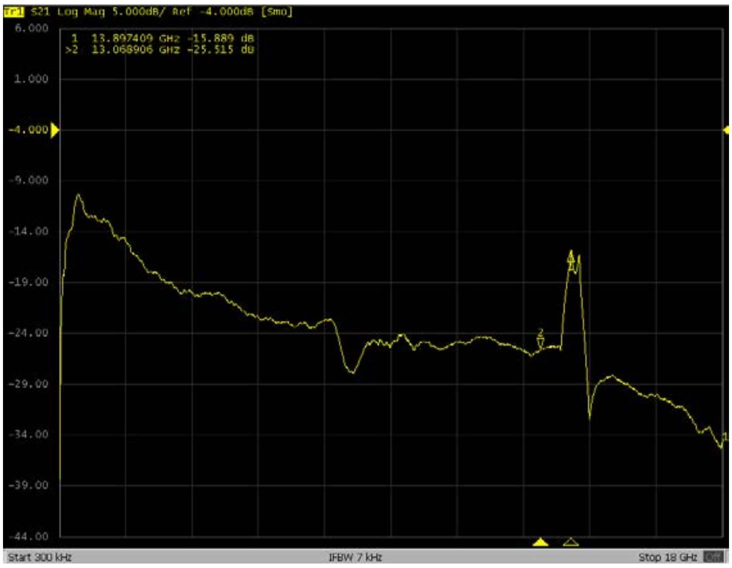

Figure 32: Full span tunability demonstration screenshot, showing photonic filtering principle.

Also, the following capabilities were shown in the acceptance test:

- Selectable input scale, showing ability for enhancing the system dynamic range.
- Manual setting of delay, gain, input scale and mode of operation within the limits of the system using software interface.
- Ability to select, edit, save and reproduce any spoofing pattern within the limits of the system.

The following conclusions can be extracted from the test plan carried out:

- The ECM system can produce broadband range radar deception just following the specifications, using optical delay line tenability.
- RGPO technique can be performed under user demand, choosing among several configurable spoofing patterns. This includes RF-to-RF gain tunability and sloping, which gives the system the ability to capture de range gate of distant radar, and delay line slopes.
- Broadband operation was demonstrated both with CW generators up to 40GHz and with complex broadband radar waveforms, using chirp, frequency hopping and other agility parameters.
- Photonic RF filtering can be performed with 1-40 GHz continuous tunability, although more efforts should be put in order to improve the selectivity of the filtering, given the very small amount of fiber optic used for the application.

Other RF dynamic tests could not be carried out because of some integration issues with a photodiode. Instead, the following measurements were taken in advance by changing the component. This measurements show the maximum RF-to-RF gain of the system, which can validate test cases not tested in 15th December 2015. This test was performed using Test Setup no 2.

<table>
<tr><th>Frequency (GHz)</th><th>RF module gain (dB)</th><th>Link gain (dB)</th><th>Global gain (dB)</th><th>Calibration offset[1]</th><th>Maximum gain (dB)</th><th>Mean gain (dB)</th></tr>
<tr><td>1</td><td>42.8</td><td>-26</td><td>16.8</td><td rowspan="3">-5</td><td>11.8</td><td rowspan="6">9.75</td></tr>
<tr><td>10</td><td>42.4</td><td>-27</td><td>15.4</td><td>10.4</td></tr>
<tr><td>18</td><td>41.6</td><td>-28</td><td>13.6</td><td>8.6</td></tr>
<tr><td>18</td><td>41.3</td><td>-28</td><td>13.3000</td><td rowspan="3">0.0</td><td>13.3</td></tr>
<tr><td>30</td><td>38.1</td><td>-29</td><td>9.1000</td><td>9.1</td></tr>
<tr><td>40</td><td>35.3</td><td>-30</td><td>5.3000</td><td>5.3</td></tr>
</table>

Table 10: In-advance measurements regarding RF dynamics

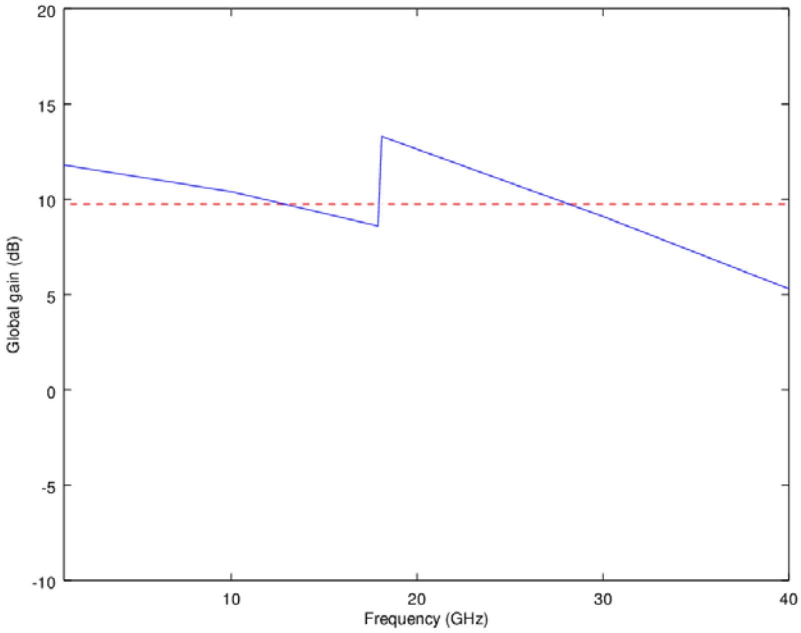

Figure 33: In-advance measurements regarding RF dynamics

[1] Calibration offset is a constant variable gain setting applied to the system for improving system flatness across the full bandwidth of operation.

5. CONCLUSIONS

5.1. Results of research

As stated before in the analysis of the results of acceptance test, the **conclusions** arising from the research effort are the following:

- The ECM system can produce broadband range radar deception just following the specifications, using optical delay line tunability.
- RGPO technique can be performed under user demand, choosing among several configurable spoofing patterns. This includes RF-to-RF gain tunability and sloping, which gives the system the ability to capture de range gate of distant radar, and delay line slopes.
- Broadband operation was demonstrated both with CW generators up to 40GHz and with complex broadband radar waveforms, using chirp, frequency hopping and other agility parameters.
- Photonic RF filtering can be performed with 1-40 GHz continuous tunability, although more efforts should be put in order to improve the selectivity of the filtering, given the very small amount of fiber optic used for the application.

The **potential applications** of the research effort performed are clear given the nature of the study: the integration of new generation ECM deception systems with features beyond the today's equipment, being able to countermeasure modern radars and future realizations which may use still more frequency agility than today modern radars.

Bringing photonics into ECM systems can open the doors for integrating advanced self-protection system into new stealth platforms such as UAVs and small aircrafts, taking advantage of its size, weight and power improvements. This possibility would be not possible for traditional electronic systems.

Also, integrated photonics are reaching 100 GHz RF transmission, which would lead to the possibility of being able to countermeasure even the latest missile guidance radar systems operating in this band.

5.2. Future lines

Following phases of the research in this line, which is in the framework of developing advanced techniques for countermeasuring radars using microwave photonics technology and its advantages, would include the following points:

- Development of photonic techniques for performing VGPO (Velocity Gate Pull-Off) countermeasure. This implies facing the challenge to produce accurate Doppler shifts (kHz regime) over optical sidebands (hundreds THz regime) without generating any spurious signals. To achieve this, transformational scientific improvements are needed in order to apply still unknown photonic techniques for broadband and low latency microwave signal treatment.
- Development of advanced angle deception techniques unsuitable for conventional electronic systems, as Cross-Eye Jamming. For this purpose, very precise signal amplitude and phase control is needed, which is only possible using optical signal processing.
- Scaling frequency operation up to W-band to cope with 94 GHz radars.
- Integration of fully developed optical nanoswitches and assessment of effect on performance.
- Being able to test the system with actual radars and assessing real-environment performance of photonic techniques compared with conventional electronic system.

APPENDIX A: LIST OF PEOPLE INVOLVED

Name	Position
Javier Martí, PhD	Main researcher
Jose F. Puche	System development / Researcher
Javier García	System development / Researcher
Xavier Jimenez	Fabrication / Mechanical design
Carlos Mateo	Mechanical design
Daniel Ramon	Electronic engineering
Fernando Cervera	Firmware development
Alejandro Leal	Software development
Francisco Climent	Software development